InLCA: Case Studies – Using LCA to Compare Alternatives

Comparative Life Cycle Assessment of Two Landfill Technologies for the Treatment of Municipal Solid Waste

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Abstract

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Goal and Scope. The potential environmental impacts associated with two landfill technologies for the treatment of municipal solid waste (MSW), the engineered landfill and the bioreactor landfill, were assessed using the life cycle assessment (LCA) tool. The system boundaries were expanded to include an external energy production function since the landfill gas collected from the bioreactor landfill can be energetically valorized into either electricity or heat; the functional unit was then defined as the stabilization of 600 000 tonnes of MSW and the production of 2.56×10^8 MJ of electricity and 7.81×10^8 MJ of heat.

Methods. Only the life cycle stages that presented differences between the two compared options were considered in the study. The four life cycle stages considered in the study cover the landfill cell construction, the daily and closure operations, the leachate and landfill gas associated emissions and the external energy production. The temporal boundary corresponded to the stabilization of the waste and was represented by the time to produce 95% of the calculated landfill gas volume. The potential impacts were evaluated using the EDIP97 method, stopping after the characterization step.

Results and Discussion. The inventory phase of the LCA showed that the engineered landfill uses 26% more natural resources and generates 81% more solid wastes throughout its life cycle than the bioreactor landfill. The evaluated impacts, essentially associated with the external energy production and the landfill gas related emissions, are on average 91% higher for the engineered landfill, since for this option 1) no energy is recovered from the landfill gas and 2) more landfill gas is released untreated after the end of the post-closure monitoring period. The valorization of the landfill gas to electricity or heat showed similar environmental profiles (1% more raw materials and 7% more solid waste for the heat option but 13% more impacts for the electricity option).

Conclusion and Recommendations. The methodological choices made during this study, e.g. simplification of the systems by the exclusion of the identical life cycle stages, limit the use of the results to the comparison of the two considered options. The validity of this comparison could however be improved if the systems were placed in the larger context of municipal solid waste management and include activities such as recycling, composting and incineration.

Keywords: Case studies; bioreactor landfill; engineered landfill; life cycle assessment (LCA); municipal solid waste (MSW) treatment

Introduction

A new approach in municipal solid waste (MSW) landfill operation might reduce the burden associated with this activity: the bioreactor landfill [1,2]. By essentially controlling the moisture content of the landfilled waste through leachate recirculation, it is possible to accelerate the degradation, or stabilization, of the waste from an original period of half a century or more to a matter of decades (10 to 20 years). This has a dual effect: 1) it reduces the temporal footprint, i.e. long-term emissions, of the landfilled waste since stabilized waste generates less emissions; and 2) it reduces the need for land since it enables the treatment of more waste in the same landfill volume (waste is transformed to gas as it is degraded, thus reducing the space it occupies and providing additional capacity). From economic and environmental standpoints, this approach is interesting because it reduces the groundwater contamination potential and makes it possible to produce a source of energy rapidly usable: landfill gas. However, since landfill gas is composed of, on average, 50% methane, this accelerated production of greenhouse gas (GHG), can compromise the environmental performance of such approach.

To evaluate if this new alternative presents a better environmental profile, it is necessary to conduct a thorough investigation of all aspects involved, i.e. to consider all the activities associated with the disposal of MSW in a bioreactor. Life cycle assessment (LCA), by considering a system in its totality, from natural resources acquisition to final disposal, can provide such information. This tool has been partially applied to evaluate MSW treatment in landfills [3,4]. But while previous studies stopped at the inventory phase of the LCA methodology, the present case study has continued to the impact assessment phase and aimed to provide a comparison of a modern or engineered landfill (hereafter noted EL) and a bioreactor landfill (hereafter noted Bioreactor) based on the evaluation of their potential environmental impacts. The study considered a hypothetical case representative of the Canadian context. It should be noted that this study does not intend to compare municipal solid waste management scenarios but only specific landfill technologies, thus the system boundaries and included unit processes have been defined with this limited goal.

1 Methodology

An LCA was performed for both types of landfill, considering as functional unit the stabilization of 600,000 tonnes of MSW (300,000 tonnes/year of waste generated and disposed of over a period of two years) and the production of 2.56×10^8 MJ of electrical energy and 7.81×10^8 MJ of heat energy. The principal function of the landfills is to stabilize MSW but, since landfill gas may be valorized into either electricity (with an internal combustion engine (ICE)) or heat (with a boiler) in the case of the Bioreactor, the production of heat and electricity was included as a secondary function through system boundary expansion. This maintained the functional equivalence of the compared systems, i.e. they both have the same outputs (stabilized waste, electricity and heat) (**Fig. 1**).

The waste composition was based on Quebec (Canadian province) MSW characterization [5] and the amount of energy considered represented the maximum recoverable energy from the Bioreactor (based on the highest landfill gas yield and an energy efficiency of 23% for the ICE and 70% for the boiler). For both systems, waste was considered stabilized when 95% of the calculated landfill gas volume is produced (as calculated from the *Solid Waste Association of North America* (SWANA) model [6]). Since the landfill gas generation rate was considered to be greater for the Bioreactor, the temporal boundary was also different, 22 years for the Bioreactor and 102 years for the EL (**Fig. 2**).

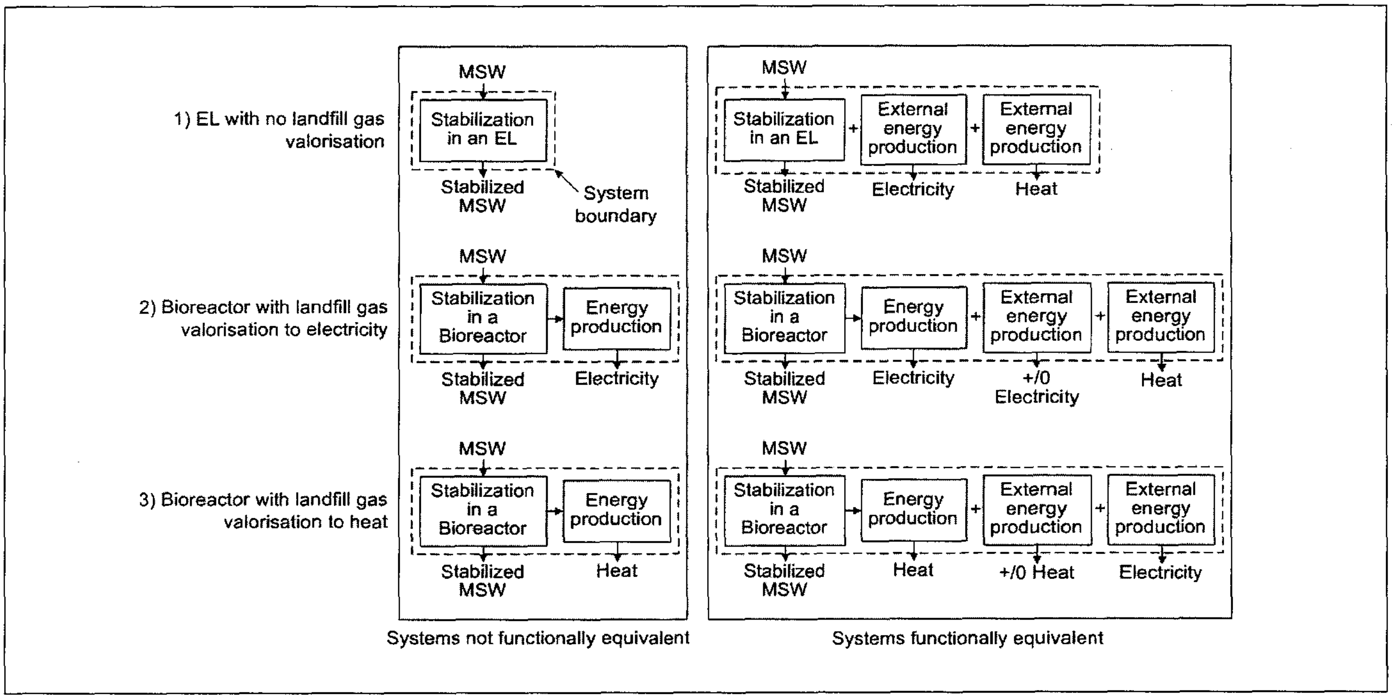

Fig. 1: System boundary expansion to maintain the functional equivalence of the compared systems

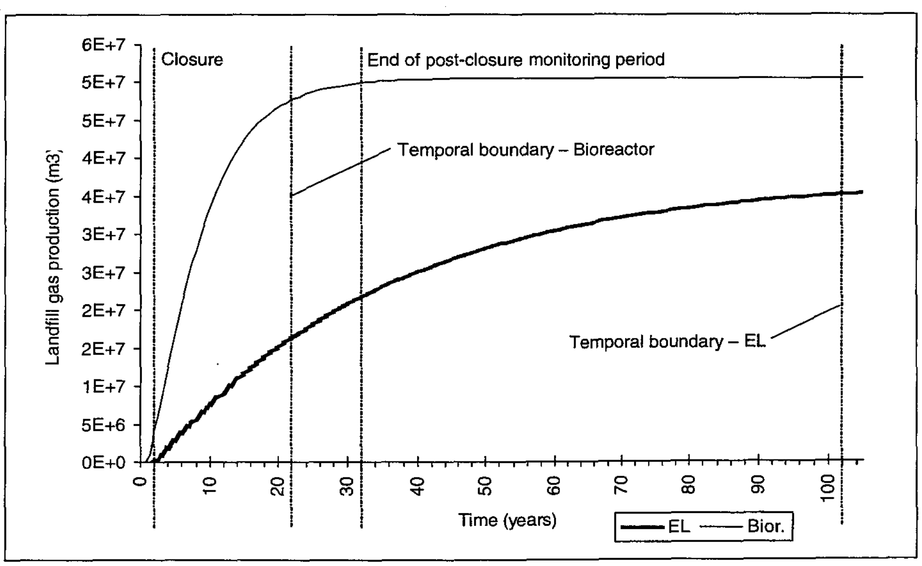

Fig. 2: Average landfill gas production and temporal boundaries

1.1 System description

The product systems were divided into 4 life cycle stages, each which several sub-stages and unit processes (**Fig. 3**). The cell construction includes the excavation of the cell and construction of a berm around the excavation, the installation of the bottom liner and leachate collection system. In the case of the EL, this stage also includes the construction of the leachate treatment system (excavation of the aeration pond, also with a berm, and installation of the bottom liner and the outflow pipe). The daily and closure operations cover the installation of the horizontal trench system, in the case of the Bioreactor, to recirculate the leachate and collect the landfill gas, the installation of the final cover at the cell's closure, and in the case of the EL, the installation of the vertical wells to collect the landfill gas. The third life cycle stage concerns the emissions associated with the leachate and landfill gas, either directly to the environment or after their collection and treatment. The last stage is made up of the external energy production processes used to supplement the systems so that their energy outputs are as indicated by the functional unit.

The unit processes that were assumed to be exactly the same for both landfills, e.g. daily cover installation, have been excluded from this comparative study. Secondary processes, the construction of infrastructure (except the landfill cell itself) and other capital goods or the human activities associated with the various unit processes, were also excluded. The maintenance of non-road equipments and other capital goods was also excluded; it was however assumed that it would make a relatively small contribution to the total environmental impacts.

The systems are described in more details in **Table 1**. Note that landfill gas is flared in the case of the EL, while it is valorized in the case of the Bioreactor. It was assumed that the energetic valorization of the landfill gas would displace natural gas production processes; hence the external energy production was considered to be from natural gas.

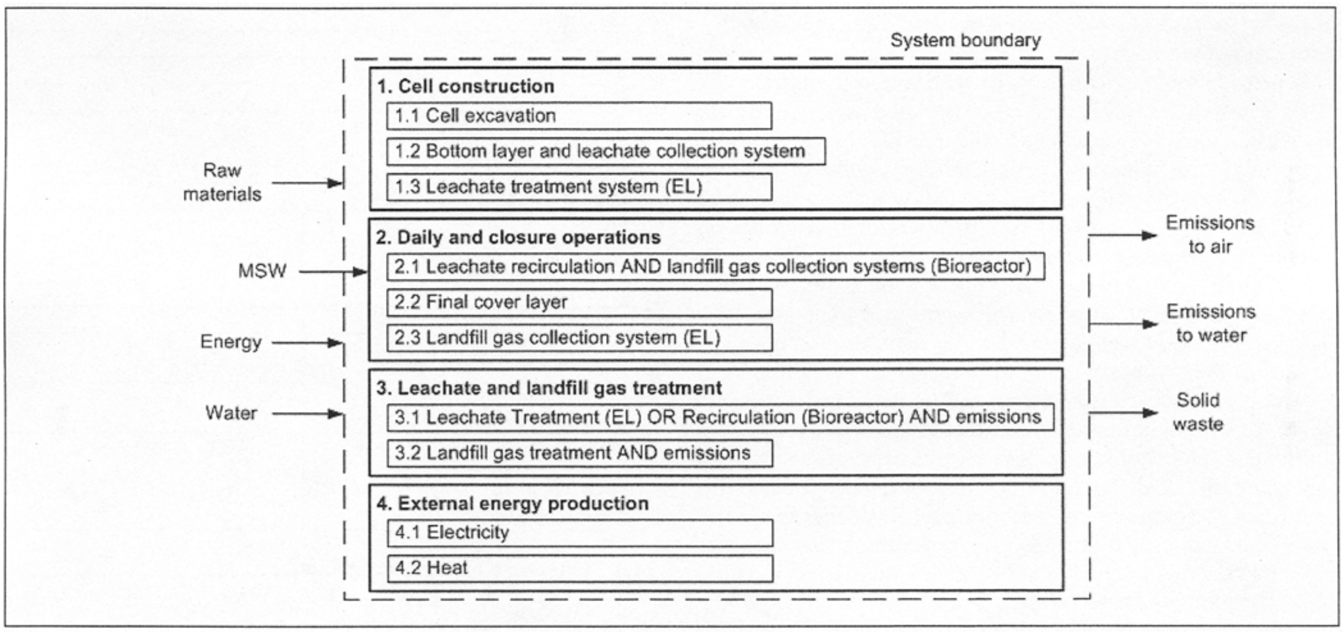

Fig. 3: Life cycle stages considered

Table 1: Systems description

	EL	Bioreactor
Bottom layer	**Geosynthetic clay liner (GCL) (PP and Bentonite), Geomembrane (HDPE), Geonet® (HDPE), Geotextile (PP)**	
Leachate collection	Gravel, HDPE pipes	
Leachate treatment	Treatment in aeration pond (Geomembrane and GCL, 50 days retention time, 200 HP for aeration) Outflow to receiving body of water (PVC pipe)	Temporary storage in vitrified steel tank with aluminium dome and reinforced concrete base Recirculation in horizontal trenches (HDPE pipes in trench filled with gravel and covered with Geotextile)
Landfill gas collection	Vertical wells (HDPE pipes in well filled with gravel and bentonite)	Horizontal trenches (the same used for the leachate recirculation)
Landfill gas treatment	Flare	ICE Boiler
Final cover layer	**Sand, Geomembrane, Organic soil**	
External energy production	Natural gas electrical power station Natural gas industrial boiler	
Excluded unit processes	Pumps and compressors for leachate & landfill gas collection Leachate treatment sludge management	Pumps and compressors for leachate & landfill gas collection Landfill gas treatment before valorization

Table 2: Data sources

Non-road equipment	NONROAD model [7]
Road transport	EMEP/CORINAIR Emission Inventory Guidebook 3rd edition [8]
Materials used	Discussions with specialized consultants in the field of landfilling
Materials production	LCA databases (IDEMAT* and Franklin Associates)
Leachate and landfill gas composition, production and treatment emissions	[6,9,10]

* Energy production and transport unit processes were replaced, when possible, by those from the Franklin Associates database to better reflect the North American context

1.2 Life Cycle Inventory (LCI)

For each unit process considered, incoming and outgoing elementary flows of the system were estimated. The sources used for these data are shown in **Table 2**. North-American data, referring to average technologies and not older than 5 years was privileged.

Several assumptions were made during the inventory analysis; only the principal ones are presented here. The cell was considered to have the same shape, depth and height for both types of landfill. The waste density was assumed to be 800 kg/m³ for the EL and 1000 kg/m³ for the Bioreactor (the faster degradation of the waste assumed for this option would result in a higher settlement of the waste before the final cover is put in place and thus provide a higher capacity for the same cell airspace volume). The daily cover volume was calculated as being 10% of the waste volume (as calculated with the EL's waste density). The post-closure monitoring period, during which both leachate and landfill gas are collected and treated, was considered to be of 30 years for both options; after this period, all activities on the site stop, i.e. the leachate accumulates in the cell and the landfill gas is emitted to the environment with partial oxidation as it passes through the organic soil layer of the final cover. The waste composition was assumed to be the same for both options, thus the composition and the calculated maximum yield obtainable (Biochemical Methane Potential, 112 m³/tonne MSW) of landfill gas are also identical. However, the effective landfill gas yield is only a fraction of this maximum since it is controlled by cell design and operation parameters. Since this fraction is not precisely known, a range of values was used to evaluate its influence on the assessment results; it was however assumed that this fraction was higher for the Bioreactor (60–90%) than for the EL (40–70%). The carbon contained in the un-produced fraction was considered as stored in the remaining waste and the CO_2 that would have been produced from this carbon, thus removed from the atmosphere and the carbon cycle, represented an environmental credit (global warming potential (GWP)). The CO_2 produced from the waste is biogenic and, as such, was not counted in the greenhouse gases inventory (GWP). In the case of the Bioreactor, the waste was assumed to have been brought to field capacity (50% w/w) at the cell's closure, from an initial moisture content of 25% w/w; this might include the addition of water if precipitations during the operation period are not enough. The maintenance of the landfill cell's components, i.e. the replacement of damaged or used parts, was not considered in the study.

The values chosen for the parameters used to calculate the volumes of leachate and landfill gas collected and emitted into the environment are shown in **Table 3**. They are the same for both options for the leachate calculations but present important differences for the landfill gas. The landfill cell's cover and bottom layer were assumed to maintain almost perfect integrity up to the end of the post-closure monitoring period, after which they slowly deteriorate and permit precipitations to leak in and leachate to leak out of the cell. The higher efficiencies of the landfill gas collection system in the case of the Bioreactor reflect the more aggressive collection strategy assumed for this option. Since all activities stop at the end of the post-closure monitoring period, the collection efficiency comes down to zero in the case of the EL; the Bioreactor shows no value for this period since the temporal boundary is reached before the end of the post-closure monitoring period.

Table 3: Leachate and landfill gas volumes calculation parameters

	EL	Bioreactor
Leachate		
Precipitation (m/m²/year)	1	
Evapo-transpiration losses (%)	60	
Runoff losses (%)		
From 0 to 1 year	5	
From 1 to 2 years	10	
After 2 years	20	
Final cover efficiency (%)		
From 0 to 1 year	0	
From 1 to 2 years	50	
From 2 to 32 years	99	
After 32 years	–0.01 per year	
Bottom layer efficiency (%)		
From 0 to 32 years	99.99	
After 32 years	–0.01 per year	
Landfill gas Collection system efficiency (%)		
From 0 to 1 year	0	0
From 1 to 2 years	50	75
From 2 to 32 years	80	90
After 32 years	0	

1.3 Life Cycle Impact Assessment (LCIA)

The LCIA method EDIP97 (Environmental Design of Industrial Products) [11] was used to evaluate the potential impacts related to the elementary flows quantified during LCI. This method is well documented and follows a problem-oriented approach. It follows the recommendations of the ISO 14 042 standard for the evaluation of the environmental impacts during an LCA. The analysis was done on characterized results; normalization and weighting of these results, which are facultative, relative and rather subjective (based on geographically biased reference values and the interested parties value-choices) steps of impact assessment, were not carried out. The impact categories considered by the EDIP97 method are global warming, stratospheric ozone depletion, acidification, eutrophication, photochemical ozone creation, ecotoxicity and human toxicity. The consumption of natural resources and production of solid wastes were individually calculated. The method does not consider impacts due to noise, odours and land use.

The global warming potential affects the environment on a global scale. The relative contribution of every greenhouse gas is represented by an equivalence factor (in g CO_2 equivalents) obtained from the emissions scenarios in the 1994 sta-

tus report from the Intergovernmental Panel on Climate Change (IPCC). The effects of the inventoried emissions are quantified over a 100-year period.

The ozone depletion potential is also a global-scale impact category. Its equivalence factors (in g CFC_{11} equivalents) for the various substances affecting the stratospheric ozone layer, are taken from the 1992/1995 status reports of the Global Ozone Research Project, a joint United Nations Environment Programme (UNEP) and World Meteorological Organization (WMO). An infinite time period is used to quantify the effects of the inventoried emissions.

Acidification and eutrophication potentials are regional-scale impact categories. The acidification equivalence factors (in g SO_2 equivalents) are based on the number of protons (H^+) that can be theoretically released by the substances considered. The eutrophication equivalence factors (in g NO_3 equivalents) are based on the number of nitrogen and phosphorus atoms present in the substances considered, whether released in the air, water and soil.

The photochemical ozone creation potential is also a regional-scale impact category. Its effects are felt within a radius of 1 000 km [11]. The equivalence factors (in g C_2H_4 equivalents) for each substance considered are taken from the 1990/1992 reports of the United Nations Economic Council for Europe (UNECE). Their values depend on the background NO_x concentration.

Ecotoxicity, i.e. the toxicity effects on organisms in the environment due to the release in the air, water and soil of anthropogenic substances, is a local-scale impact category and its potential is based on a chemical hazard screening method, which looks at toxicity, persistency and bioconcentration. Fate (distribution of substances in various environmental compartments) is also taken into account. Ecotoxicity potentials are calculated for acute and chronic ecotoxicity for water and chronic ecotoxicity for soil. Since fate is included, an emission to water can lead not only to chronic and acute ecotoxicity for water, but also for soil. Similarly, an emission to air can lead to ecotoxicity for water and soil.

Human toxicity is an impact generally felt on a local scale, and its potential is also based on a chemical hazard screening method, which looks at toxicity, persistency, bioconcentration and bioaccumulation in food and living tissues. The fate of substances in various environmental compartments is also taken into account. Human toxicity potentials are calculated for exposure via air, soil and surface water.

Ecotoxicity and human toxicity are determined by laboratory tests on living organisms or by observations on humans. Persistence in the environment is determined by a biodegradability test. Bioconcentration potential is based on the octanol-water partition coefficient.

2 Results and Discussion

2.1 Inventory analysis

The total material and energy inputs are greater for the EL (1.42×10^8 kg and 1.04×10^9 MJ) than for the Bioreactor (1.27×10^8 kg and from 3.87×10^8 to 8.23×10^8 MJ, for an average of 6.05×10^8 MJ) (**Table 4**). The amounts for the materials common to both options are associated with the size of the landfill and, since the cells have the same shape, depth and height, with the density of the landfilled waste. The higher density of the waste in the Bioreactor result in a smaller cell and in a lesser material use. The components unique to either of the systems, i.e. the PVC pipe of the leachate treatment system for the EL and the vitrified steel leachate storage tank with aluminium dome and reinforced concrete base for the Bioreactor, represent only a very small fraction of the total materials used. The assumptions made concerning the level of precipitations and the efficiency with which they enter the landfilled waste prevented the attainment, in the case of the Bioreactor, of the desired moisture content at closure (50%w/w); water must then be added to the waste. This water (2.73×10^8 kg) represents an input more than twice as important mass-wise as all other material inputs. However the origin and associated impacts of this water were not considered in the study.

In the case of the Bioreactor, the choice of valorization method for the collected landfill gas affects the energy inputs, i.e. the

Table 4: Material and energy inputs

Inputs	EL	Bioreactor – ICE	Bioreactor – Boiler
Materials (kg)			
Geosynthetic clay liner	2.57×10^5	2.03×10^5	
Geomembrane	2.23×10^5	1.82×10^5	
Geonet	3.52×10^5	3.00×10^5	
Geotextile	2.89×10^4	2.57×10^4	
HDPE pipes	2.65×10^5	6.04×10^4	
PVC pipe	4.86×10^2		
Vitrified steel tank		3.40×10^4	
Aluminum dome		1.91×10^3	
Reinforced concrete base		3.00×10^5	
Gravel	6.32×10^7	6.03×10^7	
Bentonite	1.58×10^4		
Sand	6.44×10^7	5.38×10^7	
Organic Soil	1.34×10^7	1.12×10^7	
Diesel (for non-road equipment)	3.13×10^5	2.68×10^5	
Total	$\mathbf{1.42\times10^8}$	$\mathbf{1.27\times10^8}$	
Added water		2.73×10^8	
Energy (MJ)			
External electricity	2.56×10^8	4.27×10^7	2.56×10^8
External heat	7.81×10^8	7.81×10^8	1.30×10^8
Total	$\mathbf{1.04\times10^9}$	$\mathbf{8.23\times10^8}$	$\mathbf{3.87\times10^8}$

external electricity and heat, to the system. For example, valorization to electricity results in a maximum input of heat and a less than maximum input of electricity, to account for the variability in landfill gas yield (60 to 90% of the BMP) and associated energy generation (1.71×10^8 to 2.56×10^8 MJ) (Fig. 1).

When the material and energy inputs are converted to elementary flows (**Table 5**), these are dominated for both options and for all categories, by the same substances. The amounts associated with the EL are more important than for the Bioreactor; with the only exception being for the biogenic CO_2, i.e. produced from the waste, since 1) the Bioreactor produces more landfill gas and 2) it collects and treats, i.e. combust, the gas more effectively so that the organic compounds (methane, BTEX and chlorinated compounds) contained in the gas are transformed into CO_2. The higher values shown for the Bioreactor equipped with a boiler are for substances associated with the external energy production even if the amount added to the system (3.87×10^8 MJ) is less than for the Bioreactor equipped with an ICE (8.23×10^8 MJ). This is because the production of electricity from a natural gas power station is less efficient process than the production of heat from a boiler, i.e. more natural resources are used and more emissions are released per MJ.

2.2 Impact assessment

The impact indicator results for the EL showed higher values for all impact categories considered (**Table 6**); the Bioreactor equipped with an ICE showing slightly higher values for most

Table 5: Principal elementary flows

Inputs/Outputs (kg)	EL	Bioreactor – ICE (w/o added water)	Bioreactor – Boiler (w/o added water)
Natural resources			
Sand	6.44×10^7	5.39×10^7	5.39×10^7
Gravel	6.33×10^7	6.04×10^7	6.04×10^7
Natural gas	4.07×10^7	2.29×10^7	2.47×10^7
Water	3.02×10^7	1.97×10^7	1.97×10^7
Organic soil	1.34×10^7	1.12×10^7	1.12×10^7
Crude oil	1.97×10^6	1.41×10^6	1.43×10^6
Coal	$8,67\times10^5$	4.65×10^5	4.81×10^5
Total (include resources not indicated)	$\mathbf{2.15\times10^8}$	$\mathbf{1.70\times10^8}$	$\mathbf{1.72\times10^8}$
Emissions to air			
Fossil CO_2	9.75×10^7	5.52×10^7	6.00×10^7
Biogenic CO_2	5.30×10^7	8.83×10^7	8.83×10^7
CH_4	6.30×10^6	2.17×10^6	2.18×10^6
SO_X	1.40×10^6	7.97×10^5	8.35×10^5
Total (include emissions not indicated)	$\mathbf{1.59\times10^8}$	$\mathbf{1.48\times10^8}$	$\mathbf{1.52\times10^8}$
CO_2 sink (i.e. negative emissions)	5.96×10^7	3.31×10^7	3.31×10^7
Emissions to water			
Dissolved solids	2.13×10^6	1.20×10^6	1.29×10^6
Chlorides	9.72×10^4	5.47×10^4	5.88×10^4
COD	8.72×10^4	1.70×10^4	1.82×10^4
Sulphates	7.60×10^4	4.27×10^4	4.60×10^4
Suspended solids	3.90×10^4	2.18×10^4	2.35×10^4
Oil	3.72×10^4	2.09×10^4	2.25×10^4
Total (include emissions not indicated)	$\mathbf{2.51\times10^6}$	$\mathbf{1.36\times10^6}$	$\mathbf{1.46\times10^6}$
Solid waste			
Solid waste (unspecified)	4.16×10^6	2.31×10^6	2.48×10^6
Leachate treatment sludge	2.06×10^5	0	0
Total (include wastes not indicated)	$\mathbf{4.42\times10^6}$	$\mathbf{2.36\times10^6}$	$\mathbf{2.53\times10^6}$

Table 6: Impact indicator results

Scale	Environmental impact category	Unit	EL	Bioreactor – ICE	Bioreactor – Boiler
Global	Global Warming Potential – 100 years (GWP)	g CO_2 eq.	1.98E+11	7.78E+10	8.24E+10
	Ozone Depletion Potential (ODP)	g CFC_{11} eq.	8.38E+2	3.49E+2	2.61E+2
Regional	Acidification Potential (AP)	g SO_2 eq.	1.67E+9	1.06E+9	1.03E+9
	Eutrophication Potential (EP)	g NO_3 eq.	5.46E+8	4.93E+8	3.47E+8
	Photochemical Ozone Creation Potential (POCP)	g C_2H_4 eq.	5.90E+7	3.01E+7	1.98E+7
Local	Ecotoxicity – Water, Chronic (ETWC)	m^3 water/g	1.20E+9	6.62E+8	7.12E+8
	Ecotoxicity – Water, Acute (ETWA)	m^3 water/g	1.19E+10	6.63E+9	7.12E+9
	Ecotoxicity – Soil, Chronic (ETSC)	m^3 soil/g	9.84E+6	4.53E+6	5.43E+6
Local	Human Toxicity – Air (HTA)	m^3 air/g	2.88E+12	1.64E+12	1.14E+12
	Human Toxicity – Water (HTW)	m^3 water/g	2.85E+8	1.61E+8	1.73E+8
	Human Toxicity – Soil (HTS)	m^3 soil/g	3.24E+6	1.80E+6	1.03E+6

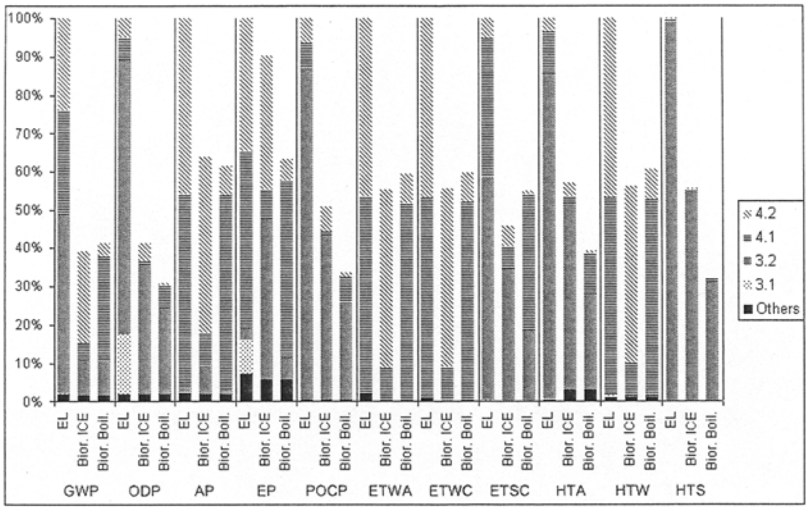

Fig. 4: Relative impact assessment scores for each option by impact category and life cycle stage

categories than the Bioreactor equipped with a boiler. However, the same life cycle stages dominate the impact for all categories and for all options (**Fig. 4**). The external production of energy (life cycle stages 4.1 and 4.2) comes in first with an average contribution of 55% of the impacts for the EL and from 51% (ICE) to 63% (boiler) for the Bioreactor. While the treatment and fugitive release of landfill gas (stage 3.2) is second, being responsible for, on average, 41% of the impacts for the EL and from 46% (ICE) to 34% (boiler) for the Bioreactor. There is a somewhat important contribution of the leachate treatment stage (3.1) for the EL to the ozone depletion category (16%), due to the volatilization of chlorinated organic compounds (CCl_4) during the stay in the aeration pond prior to release to the receiving body of water, and to the eutrophication category (9%) due to the ammonia in the leachate, partially transformed to nitrate during aeration which also contribute to this category. The other life cycle stages, taken together, have a very small if not negligible contribution.

The higher impacts associated with the EL are due to 1) the production of more external energy since the collected landfill gas is not valorized and 2) the lower efficiency of the extraction system and slower rate of landfill gas generation resulting in a larger fraction of the gas (51%) being emitted to the environment without treatment since it is either not collected or generated after the end of the post-closure monitoring period (Fig. 2). The differences between the impacts of the Bioreactor equipped with an ICE or a boiler a due to 1) the emissions for both external energy production processes are similar but the production of electricity from natural gas being less efficient than the production of heat, the impacts associated with electricity are higher than those associated with heat even when considering the amounts produced and 2) the difference in treatment efficiency, i.e. the ability to transform the trace organic compounds (BTEX, chlorinated compounds) present in landfill gas into more harmless forms (CO_2, HCl, SO_2), and emission factors (NO_2, CO, PM) for both technologies, the boiler being more efficient and cleaner.

Since the length of the post-closure monitoring period played a critical role in the assessment of the EL, 38% of the landfill gas is produced after the end of this period and emitted to the environment without being treated, i.e. flared, it was decided to evaluate the influence on this parameter on the results. To measure the extent of this influence, the post-closure monitoring period was extended to the temporal boundary (102 years) and only the treatment of the collected landfill gas and leachate was considered, all other aspects of the system remaining the same. This resulted in a very important reduction in the landfill gas emitted to the environment, from 51% of the total volume produced to only 20% (the bioreactor only emits 12% of its landfill gas due to its more efficient extraction scheme). More of the methane and other organic compounds present in the landfill gas is then transformed into biogenic CO_2 and is not accounted for in the impact assessment, resulting in a sharp decrease of most impact indicators (**Fig.** 5, the scores for the Bioreactor are unchanged and can be used as reference), the only ones not affected are the acidification and water related ecotoxicity and toxicity categories, being essentially only associated with the external energy production. A lesser landfill gas production which is flared, a treatment method somewhat between the ICE and boiler in terms of destruction efficiency and emission factors, advantages the EL even when considering the less efficient extraction system, its contribution to the impacts being now inferior to the one of the landfill gas in the case of the Bioreactor equipped with an ICE (the only exception is for the photochemical ozone potential since the CO emission factor for the flare is almost twice that of the ICE). This causes the impact indicator results of the EL, for the toxicity related to air and soil categories, to even slip under the one of the Bioreactor equipped with an ICE. However, the gain provided by the treatment of a larger fraction of the produced landfill gas is partially countered by the treatment and associated emissions of a larger volume of leachate, increasing the impact to the relevant categories (ozone depletion and eutrophication), and even in this hypothetical situation, the Bioreactor still presents a better environmental profile, its impact being on average 73% (ICE) and 63% (boiler) that of the EL for the impact categories considered.

3 Conclusions and Recommendations

The life cycle assessment methodology was used to compare the treatment of municipal solid waste in engineered and bioreactor landfills and identified the EL as, on aver-

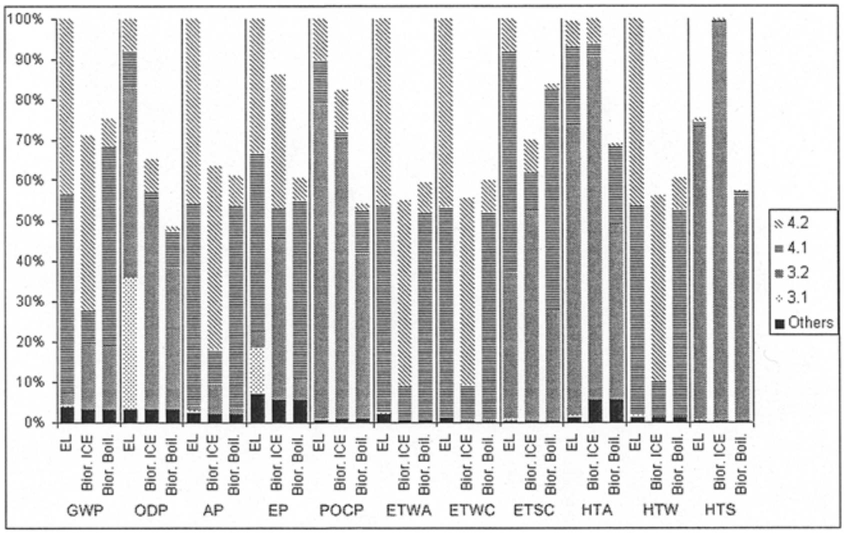

Fig. 5: Relative impact assessment scores with the modified EL option (post-closure monitoring period = temporal boundary)

age, using 26% more natural resources, generating 82% more solid waste and 91% more potential environmental impacts. In the case of the Bioreactor, valorization of landfill gas to electricity with an internal combustion engine and to heat with a boiler provided similar environmental profiles (1% more raw materials and 7% more solid waste for the boiler option but 13% more impacts for the ICE option).

However, electricity production being a major contributor to the impacts associated with both options, it would be interesting to quantify and include the energy needs of the excluded processes, i.e. the pumps and compressors used to collect the leachate and landfill gas, since the volumes considered are larger for the Bioreactor but the period of use is longer for the EL. To increase the validity of the comparison, the study would have to include the leachate treatment sludge management in the case of the EL and the water that must be added to the waste in the Bioreactor. The latter could even lead to another environmental credit since it could be contaminated water, e.g. wastewater [2], and the Bioreactor would then behave as an alternative treatment system. The influence of parameters other than the length of the post-closure monitoring period (bottom layer and final cover efficiencies, landfill gas extraction scheme) would also have to be studied. Finally, the compared systems would have to be placed in the larger context of municipal solid waste management and consider activities such as recycling, composting and incineration. However, the comparative nature of this study and its methodological implications (simplification of the systems by the exclusion of the identical life cycle stages and system boundaries expansion to include the secondary energy production function) should not be forgotten since the use of the results in another context could result in erroneous conclusions.

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References

[1] Campman C, Yates A (2002): Bioreactor Landfills: An Idea Whose Time Has Come. MSW Management 12 (06) 70–81

[2] Reinhart DR, McCreanor PT, Townsend T (2002): The Bioreactor Landfill: Its Status and Future. MSW Management & Research 20, 172–186

[3] Norstrom JM, Barlaz MA, Bourque HJ (2001): Life Cycle Inventory Comparison of a Bioreactor Landfill and a Traditional MSW Landfill in Sainte-Sophie, Quebec, 6th Annual Landfill Symposium, SWANA, San Diego, June 18–20

[4] Barlaz MA, Ozge Kaplan P, Ranji Ranjithan S (2003): Using Life Cycle Analysis to Compare Solid Waste Management Alternatives Involving Recycling, Composting and Landfills 13 (04) [on line]: http://www.forester.net/mw_elements04_lca.html

[5] CHAMARD – CRIQ – ROCHE (2000): Caractérisation des matières résiduelles au Québec. Final Report PR-99101-01, Cap-Rouge, Canada

[6] Ecobalance Inc. (1999): Life Cycle Inventory of a Modern Municipal Solid Waste Landfill. 407 pp. Report prepared for the Environmental Research and Education Foundation

[7] U.S EPA's Office of Transportation and Air Quality. Modeling and Inventories – NONROAD Model (Off-road Vehicles, Equipment, and Vehicles). [on line]: http://www.epa.gov/otaq/nonrdmdl.htm

[8] EEA (European Environment Agency) (2002): EMEP/CORINAIR Emission Inventory Guidebook, 3rd edition [on line]: http://reports.eea.eu.int/technical_report_2001_3/en

[9] Sich B, Barlaz M (2000): Process Model Documentation: Calculation of the Cost and Life-Cycle Inventory for Waste Disposal in Traditional, Bioreactor and Ash Landfills. North Carolina State University

[10] U.S. EPA (2002): Solid Waste Management and Greenhouse Gases, A Life-cycle Assessment of Emissions and Sinks (Section 7), 2n ed, EPA 530-R-02-006. [on line]: http://yosemite.epa.gov/OAR/globalwarming.nsf/content/ActionsWasteReports.html

[11] Wenzel H et al. (1998): Environmental Assessment of Products – Vol 1: Methodology, Tools and Case Studies in Product Development. Kluwer Academic Publishers

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